Hydrogen Mixtures on Industrial Burners Designed for Natural Gas

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Abstract

Increasingly industries which are reliant on natural gas combustion are looking to gaseous hydrogen (H2) as a fuel to reduce their carbon dioxide footprint. While nearly all industrial burners can be designed or modified to burn hydrogen or hydrogen fuel mixtures, this modification can be expensive and represents a hurdle for early adoption of hydrogen combustion. Current research has investigated the effects of grid level injection of hydrogen at low percentages (0-50%) on select few industrial burners designed for natural gas. While these studies have shown promising results, the burner geometries do not represent the most common industrial burner types, excluded higher percentages of hydrogen mixtures (50-100%), and did not adequately investigate the thermal effects on the burner itself. Lab testing carried out by three Honeywell burner test facilities will be presented in this report for the three most common fuel and air mixing strategies used by industrial burners: nozzle mix, cup mix, and premix/partial premix. This testing shows that at higher percentages of hydrogen mixtures the flame's heat release pattern is concentrated and local flame temperature increases near the burner fuel nozzle. This concentration of heat release reduces the effectiveness of excess air in reducing local flame temperature due to decreased heat transfer. At similar excess air levels, this rise in local flame temperature will increase NOx compared to natural gas by 25-140% depending on burner type and hydrogen percentage in the fuel. Component temperatures will also increase at similar excess air levels with hydrogen combustion, and depending on the burner design, can cause a severe reduction in component life. If excess air can be increased enough, and the industrial process can accommodate a change in oxygen levels, the higher NOx and excess component temperatures found with high hydrogen fuel mixtures can be eliminated. Not all industrial burners originally designed for natural gas will be able to burn high hydrogen fuel mixtures without a reduction in service life. The most promising industrial burner designs for utilizing high hydrogen fuel mixtures (>50%) without modification examined by this report, use a nozzle mix and maintain a high air velocity throughout the burner.

Introduction

In order to meet commitments made in the Paris Climate Agreement and COP2, governments around the world are ramping up their greenhouse gas reduction strategies. Some examples of the strategies employed include taxing emitted carbon prices and increasing investment in alternative fuels such as hydrogen. According to the International Energy Agency's World Energy Outlook 2021, 17 governments have published low-carbon hydrogen strategies and 20 more countries are developing them. These efforts will enable hydrogen combustion to become an attractive option for industries reliant on traditional hydrocarbon fuels. Most industrial burners can be designed and modified to burn any mixture of hydrogen and hydrocarbon, and this type of modification is common for burners utilizing hydrocarbons other than natural gas as a fuel (propane, butane etc.). However, these modifications can be expensive and adds to the hurdle for hydrogen adoption. Research by Leicher and coworkers [1] has shown that certain natural gas burners can tolerate hydrogen mixtures up 50% in the fuel supply without major ill effects on the process. While the study by Leicher and coworkers has provided promising results, the burner geometry did not represent the most common industrial burner types, did not investigate higher percentages of hydrogen mixtures (50-100%) and did not adequately investigate the thermal effects on the burner itself. This report seeks to fill these gaps by examining more of the effects of providing hydrogen, at any percentage, to the fuel supply of industrial burners designed for natural gas. We will do this by examining industrial burner testing conducted by multiple Honeywell burner test labs. The testing will be categorized by the fuel and air mixing strategy used by the burner, and the analysis will be limited to the effects that can be attributed completely to the burner fuel and air mixing strategy. In this way the conclusions drawn can be applied to any industrial burner that uses the same mixing strategy. The three fuel and air mixing strategies evaluated will be nozzle mix, cup mix, and premix/partial premix. These three mixing strategies are used in a large majority of industrial burners. By studying the effect of hydrogen on all three mixing strategies, a more complete picture of the effect of hydrogen blends on industrial burners can be seen.

For the purposes of this report, an industrial burner is defined as any burner that produces heat for industrial processes outside of the chemical/refinery industry. These are most commonly natural gas fired with a packaged or remote blower providing combustion air. The burners used in chemical/refinery industry deal with much higher fuel pressures and the combustion air is normally natural draft, so they will be excluded from this report as they have additional considerations. Industrial burners also include natural gas burners where the oxidant is pure oxygen rather than air, but this report will limit the discussion to burners that use air as an oxidant. The typical applications for industrial burners are wide and varied including steel strip annealing, baking ovens, regenerative thermal oxidizer etc. No matter the application, first and foremost an industrial burner is designed to meet its application requirements on heat output, emissions, and heat release pattern. An industrial burner's fuel and air mixing strategy is critical to meeting these application requirements.

Each of the three fuel and air mixing strategies covered in this report have advantages and disadvantages depending on the application requirements. To explore each mixing strategy's reaction to hydrogen combustion each strategy will be evaluated on its, flame stability, thermal turndown, and emissions. The mixing strategy is not the only feature of an industrial burner that affects the three items above, but it does have the largest effect. Each design will be evaluated under the condition that no physical modification be made, and the fuel could be natural gas, hydrogen, or any mixture of the two.

Hydrogen Combustion Properties

Compared to natural gas hydrogen has lower density, higher diffusivity rate with air, higher flame speed, wider flammability limits, lower heating value per unit volume, and lower minimum ignition energy. Much has been written about hydrogens chemical and combustion properties, but for the purposes of analyzing hydrogens effect on burners a simple comparison of key combustion properties for hydrogen and natural gas will suffice, see **Table 2.** In **Table 2.** each hydrogen property has a % difference when compared to the same natural gas property, with up and down arrows indicating if the value is lower or higher.

Table 2. Comparison of Key Combustion Properties of Hydrogen Gas and a Typical Natural Gas

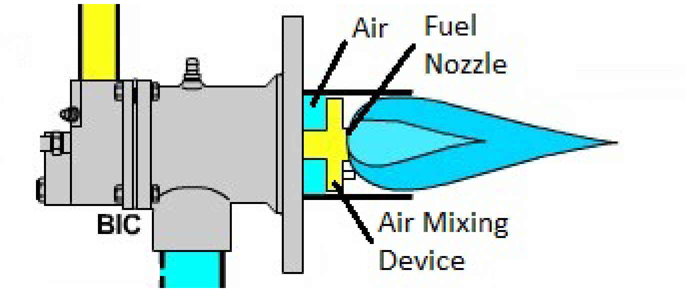
Parameter	**H_2**	**Natural Gas**	**% Difference**
Specific Gravity[2]	0.0696	0.592	▼ 158%
Diffusion Coefficient in Air STP (in^2/s)[3]	0.105	0.031	▲ 109%
Flame Velocity in Air (ft/s)[2]	9.3	1.00	▲ 161%
Lower Flammability Limit (% fuel gas by volume)[2]	4.00	4.3	▼ 7%
Upper Flammability Limit (% fuel gas by volume)[2]	74	15	▲ 133%
Higher Heating Value (HHV) (Btu/ft^3)[*],[2]	325	1040	▼ 105%
Lower Heating Value (LHV) (Btu/ft^3)[*],[2]	275	939	▼ 109%
Stoichiometric Air Fuel Ratio (vol air/vol fuel)[*],[2]	2.38	9.8	▼ 121%
Gross Heat Release per Volume of Air (Btu/ft^3)[*],[2]	136	106	▲ 25%
Minimum Ignition Energy (mJ)[3]	0.017	0.28	▼ 177%
Auto Ignition Temperature (F)[2]	1062	1170	▼ 10%
Flame Temperature (F)[2]	3821	3562	▲ 7%

[*] [93%C_4H_4] [4.79%C_2H_6] [0.35%C_3H_8]-Chromatograph Analysis from ANR Storage Company

Nozzle Mix

Nozzle mix is a very common strategy used by industrial burners to mix the fuel and air. These burners mix the fuel and air at the point of ignition with a fuel nozzle and an air mixing device. Nozzle mixing creates stable flames that can operate under a wide range of air fuel ratios. This type of industrial burner typically has good thermal turndown, anywhere in the range of 8:1, to 50:1. Nozzle mix burners thermal turndown and flexibility comes at a cost to the quality of the fuel and air mixture.

Figure 1. Nozzle Mix BIC Burner Cross Section



The critical devices of a nozzle mix burner are the fuel nozzle and the air mixing device. The fuel nozzle has integral orifices which have three primary functions: to deliver the right amount of fuel, to deliver the fuel at the right velocity, and deliver the fuel in the desired direction to shape to the flame. In the same way the air mixing device controls the air to form the air fuel mixture at the point of ignition. The required amount of fuel and air through the nozzle is dictated by the chemistry of the fuel and oxidant as well as the desired furnace conditions. The velocity of the fuel and air during mixing is a major factor in determining the quality of the mixture and the thermal properties of the flame. If burner firing rate or capacity is to be maintained, when hydrogen is supplied to a nozzle mix burner the velocity of the hydrogen will be almost 3 times as high as the same nozzle supplied with natural gas. This is primarily a function of hydrogen's having a lower heating value, when compared to natural gas (see **Table 2.**). For the same heat output to be maintained a higher volumetric flow rate is required through the fuel nozzle.

Nozzle Mix- Flame Stability on Hydrogen

Can a nozzle mix burner designed for natural gas remain lit and stable with nearly 3-fold increase in fuel velocity/fuel flow rate? If the fuel was natural gas, for a majority of burners the answer would be no. The conditions that sustain the flame could not be maintained with such a wide swing in velocity and flow rate. Hydrogen, however, has unique properties that do allow the flame to be maintained under these conditions.

One of these properties that allows the flame to be maintained at a much higher fuel flow rate is hydrogen's stoichiometric air fuel ratio. This is the volume of air required to completely burn one volume unit of fuel. For hydrogen the stoichiometric ratio is 2.38, and for natural gas that ratio is 9.8 (**Table 2.**). For example, to burn 1,000 ft^3 of hydrogen 2,380 ft^3 of air is required. To burn that same quantity of natural gas 9,800 ft^3 of air is required. Imagine a situation where a nozzle mix burner designed for natural gas is supplied with hydrogen with no changes in the control scheme; the fuel flow rate increases by a factor of 2.91, but the amount of air remains the same. If our hypothetical nozzle mix burner was designed run stoichiometric (0% excess air, or $\emptyset = 1.0$), it would be flowing 1000 ft^3 of natural gas, and 9,800 ft^3 of air. If this burner was switched to hydrogen, it would be flowing 2910 ft^3 of fuel, but still running 9,800 ft^3 of air. This would bring the excess air to 41% or $\emptyset = 0.71$. This not the same air fuel ratio as originally designed but most nozzle mix burners will remain lit and still output heat due to their flexibility in viable air fuel ratios. The other property that helps maintain this flame under high fuel flow rate, is hydrogen's high diffusivity coefficient. Hydrogen has one of the highest diffusivity coefficients in air, 0.105 in^2/s compared to natural gas at 0.031 in^2/s (**Table 2.**). This allows hydrogen to mix with air at a much higher rate compared to natural gas. Overall hydrogen mixes very well with air and any strategy developed to mix natural gas and air will only improve when using hydrogen.

Most nozzle mix burners will remain lit and stable when switching from 100% natural gas to 100% hydrogen based on the explanation above. However, one of the most critical factors when burning high hydrogen mixtures or 100% hydrogen is how the burner deals with the extra heat that the hydrogen flame creates in the burner. It will be shown that the hydrogen flame's heat release pattern is more concentrated when compared to natural gas flames. The hydrogen flame has a higher local flame temperature near the point of fuel and air injection. The main mechanism for this behavior depends on the design of the burner nozzle and the way in which the flame is anchored [7]. The two dominant mechanisms for this hydrogen flame concentration relate to hydrogen's wider flammability limit, and its higher flame velocity. For some nozzle mix burners the dominant mechanism will be the rate of fuel and air mixing. When keeping air flow constant and switching to hydrogen as a fuel, the rate at which a flammable mixture is maintained and its location relative to the burner nozzle can be illustrated by looking hydrogens flammability limits. **Table 2.** Lists hydrogen's flammability limits as 4-74% hydrogen by volume, compared to 4.3-15% natural gas by volume. In a nozzle mix burner, the fuel exiting the orifice in the fuel nozzle is combined with air and ignited. If the fuel can sustain flame at a higher percentage of fuel, as in hydrogens case, a flammable mixture downstream of the fuel nozzle and air mixing device will be created more quickly. This leads to a concentrated region of high local flame temperature which imparts more heat through radiation and convection to the burner components. The other major mechanism for the hydrogen flames concentrated heat release pattern is hydrogen's higher flame velocity, see **Table 2**. Due to the way the flame is anchored in certain nozzle mix burners the flame will exhibit some characteristics of a premixed flame. In premixed flames the flame will burn at the point where the mixture velocity equals the flames velocity. Since hydrogen's flame velocity is much higher the flame can burn closer to the fuel nozzle where the exit velocity is higher. The result is the same as the previous mechanism, burner component temperatures are elevated due to the concentrated region of high local flame temperatures.

This concentration of hydrogen flames can be seen by examining the pictures of the flame as the H2 content is increased. **Figure 2**. and **3.** were taken from Test Setup 1. This test setup utilized a nozzle mix burner that is applied primarily in air heating applications. Test Setup 1 was run on a water backed fire tube furnace with emissions monitoring equipment sampling at the stack, in the Muncie, Indiana test facility. The burner was run at 0.500 MMBtu/hr (146 kW) from 0 to 100% hydrogen at varying levels of excess air.

Figure 2. Nozzle Mix Burner-100% Natural Gas at 0.500 MMBtu/hr with 52% Excess Air

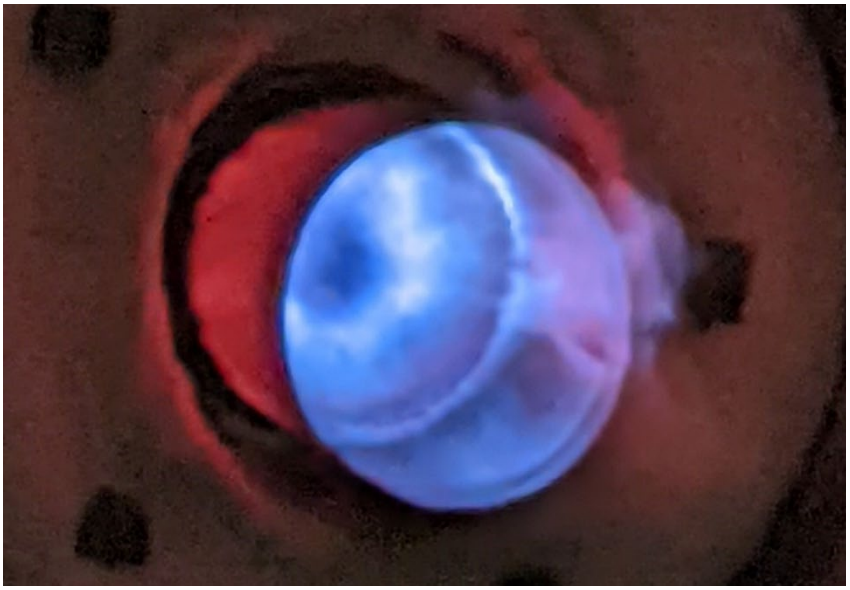
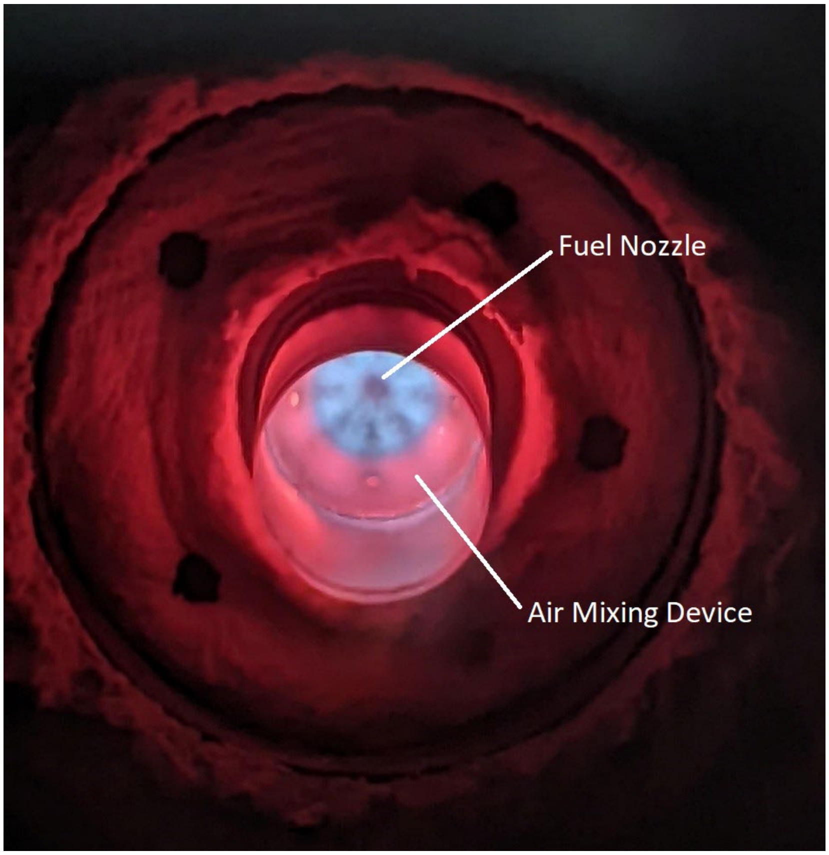


Figure 3. Nozzle Mix Burner-75% Hydrogen 25% Natural Gas at 0.500 MMBtu/hr with 46% Excess Air



It can be seen by comparing **Figure 2.** and **Figure 3.** that when the burner is operating at similar excess air levels, the hydrogen flame is anchored much farther back in the burner (nearer to the fuel nozzle at the center) and is more concentrated. This changes the heat release pattern of the flame significantly.

It can also be seen from the color change of the metal components from **Figure 2.** to **3.** that the concentrated heat release pattern of the hydrogen flame transfers more heat to the air mixing device for this burner. In some cases, this excess temperature can reduce the service life of the burner. The temperature data in **Figure 5.** was collected by the Vilvoorde, Belgium facility on a nozzle mix burner firing into the open air. The temperatures shown were taken from an air mixing device similar to the one shown in **Figure 2.** And **Figure 3.**

Figure 5. Air Mixing Device (Mixing Cone) Temperatures from a Nozzle Mix Burner at Varying Capacities and Hydrogen and Natural Gas Mixtures

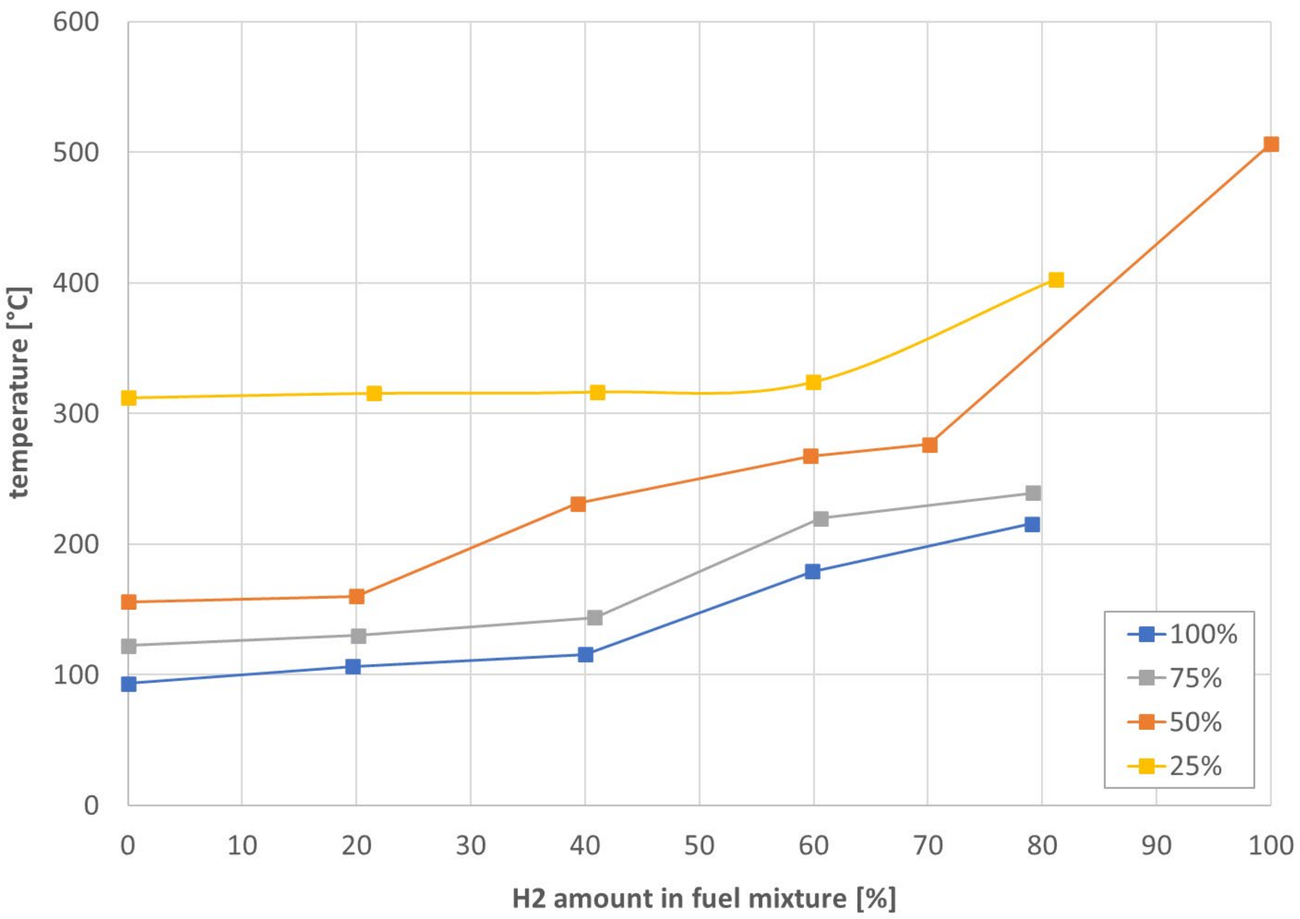


Figure 5. shows that for nozzle mix burners using the type of air mixing device shown in **Figure 2.** and **Figure 3.** the excess temperature from high hydrogen mixtures will increase the component temperatures by about 210 °C, this increase in temperature can severely impact the burner's service life depending on material choice.

Whether the burner's internal components can sustain this increased heat load has a lot to do with the overall burner design, not just the fuel and air mixing strategy. Burners that use the nozzle mix strategy are applied in a wide variety of applications, and each application has different requirements on flame length, flame velocity, emissions etc. High velocity nozzle mix burners maintain a high air velocity out of the burner and into the application and therefore are more able to transfer the extra heat from hydrogen combustion away from the burner's internal components. In **Figure 6.** component temperatures for a high velocity nozzle mix burner firing into the open air were taken by the Lotte, Germany test facility. Thermocouples were placed at various intervals along the burner's discharge sleeve, in the air mixing device, and at the end of its fuel nozzle.

Figure 6. High Velocity Nozzle Mix Component Temperatures taken by the Lotte, Germany Testing Facility

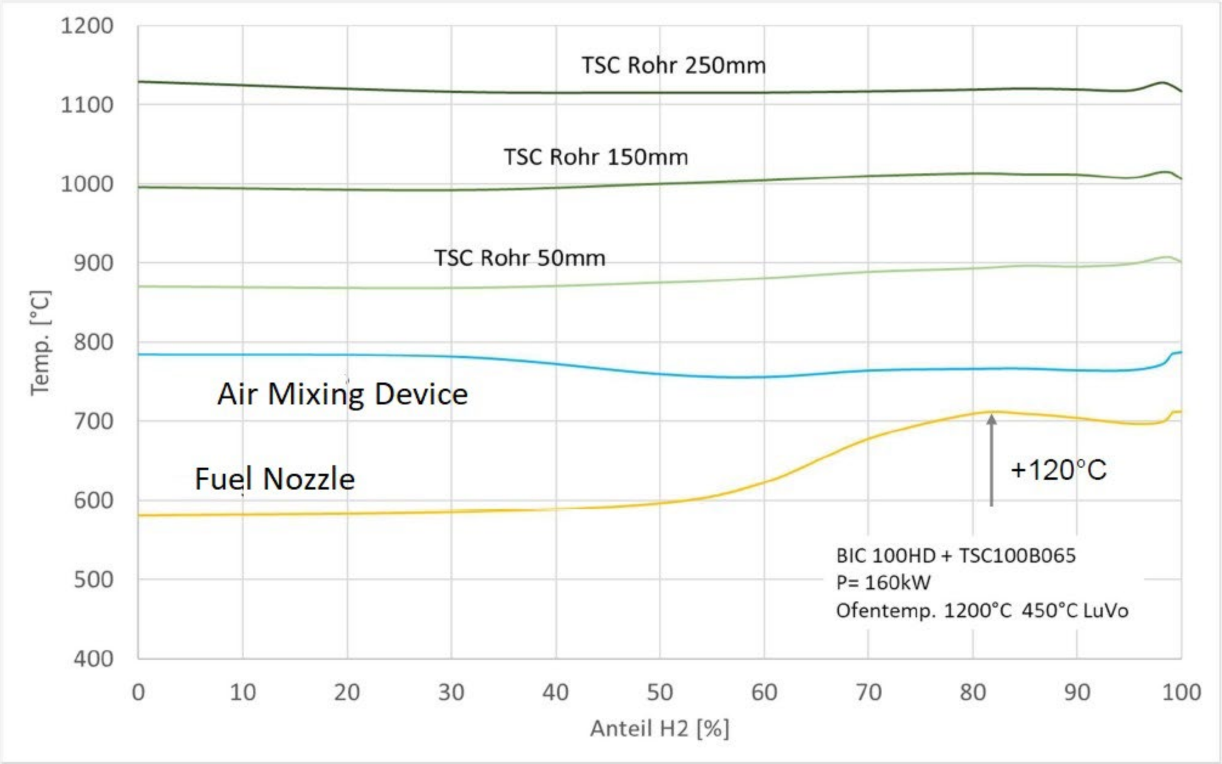
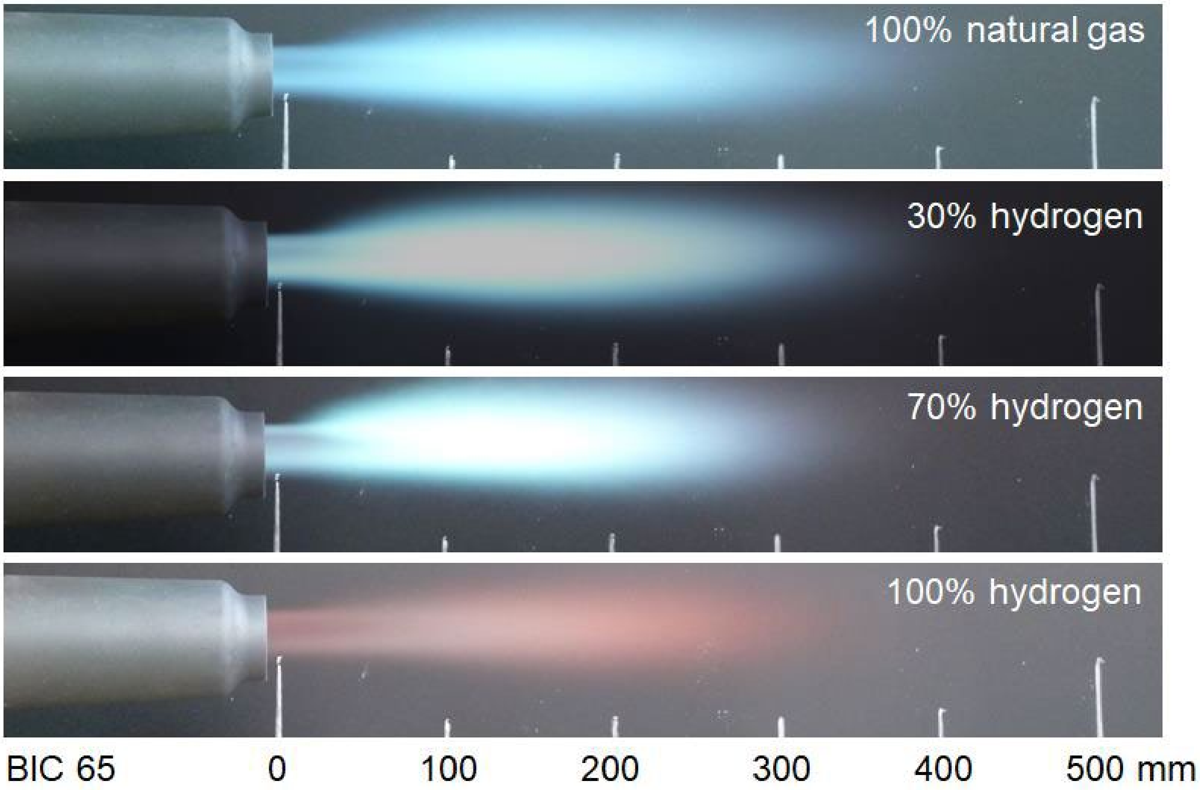


Figure 6. shows that with high velocity nozzle mix burner the increase in component temperatures are not as severe as with some nozzle mix burner types (**Figure 5.**). **Figure 6.** shows a 17% increase in fuel nozzle temperature at higher hydrogen mixtures, which is not likely to cause significant issue with burner's service life.

Typical flame shapes for a high velocity nozzle mix burner can be seen in **Figure 7.** These pictures were taken by firing the burner in the open air at a capacity of 0.307 MMBtu/hr (90 kW) with 5% excess air at the Lotte, Germany test facility. These images show a decrease in flame luminosity as increasing amount of hydrogen are added to the fuel, as well as a change in the visible color from blue to orange/red. The visible flame geometry is largely unaffected with the addition of hydrogen. The overall flame shape and flame length is nearly unchanged. This effect is seen across all mixing types which are the subject of this report (**Figures 7, 12, and 16**).

Figure 7. Typical Flame Shapes for High Velocity Nozzle Mix Burners at Varying Hydrogen Mixtures



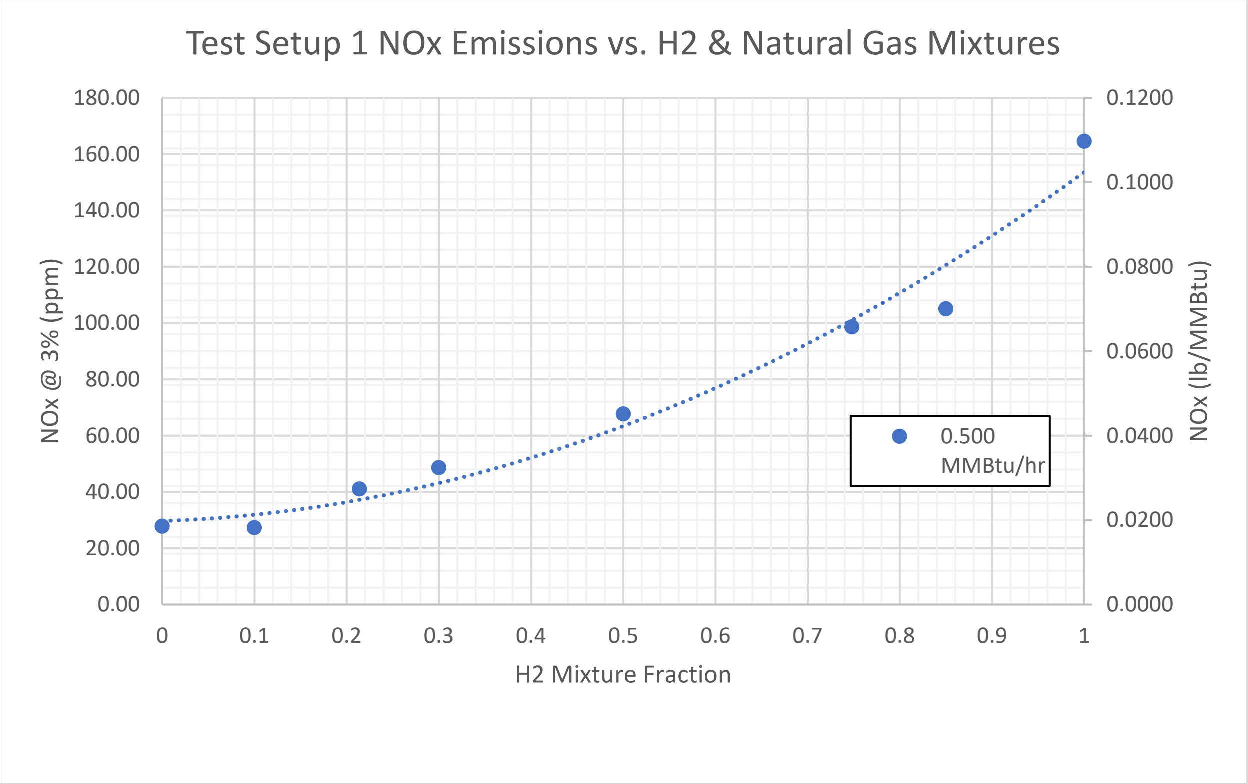
Nozzle Mix- Thermal Turndown

The thermal turndown of a nozzle mix burner firing hydrogen is not significantly different than the same burner firing natural gas. Due to the reasons described above a nozzle mix burner running hydrogen can operate in same range of air flow rates as a burner designed for natural gas and remain lit and stable. Forgetting all other considerations (heat buildup, resonance) addition of hydrogen should extend the flexibility of the nozzle mix burner. This could be due to hydrogen's high diffusivity coefficient in air which allows higher percentages of excess air to be used and still maintain proper mixture properties.

Nozzle Mix- Emissions

Overall design of the burner has the largest effect on the emissions of that burner, but some conclusions can still be drawn about the emissions of a burner that uses the nozzle mix strategy and burns hydrogen. NOx is an emission that needs to be limited in combustion due to its hazard to human health. In most cases the NOx produced will increase when adding any percentage of hydrogen to a nozzle mix burner. How much the NOx increases depends on the overall burner design and amount of hydrogen in the fuel mixture. NOx formation is strongly linked to flame temperature and residence time. The hydrogen flames concentrated heat release pattern reduces the quenching effect of excess air because there is less total heat transfer away from the flame, which increases local flame temperatures. When local flame temperature goes up, more NOx is produced. At higher hydrogen mixtures if the metal temperatures increase enough this will further reduce the heat transfer potential of the excess air by increasing overall mixture temperature. This will cause a further increase in NOx formation. Emissions data taken from Test Setup 1 can be seen in **Figure 8.**

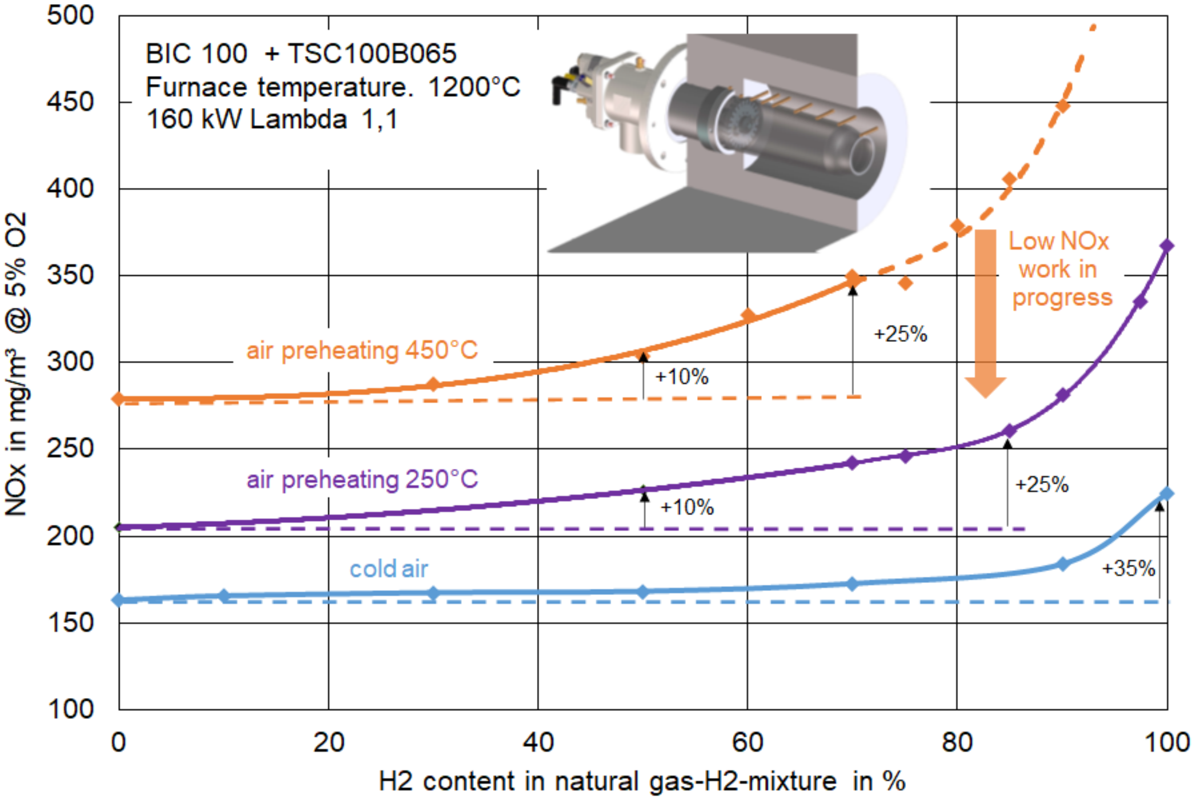
Figure 8. Test Setup 1 Nozzle Mix Emissions for Increasing H2 Mixtures.



The nozzle mix burner from Test Setup 1 showed a 135 ppm (140%) increase in NOx emissions between 100% natural gas and 100% hydrogen at a set excess air setting.

The size of this effect depends largely on the overall design of the nozzle mix burner. As mentioned previously, high velocity burners can more quickly dissipate the extra heat that comes with hydrogen flames so the increase in NOx is typically lower for those burner types, around 35% (**Figure 9.**)

Figure 9. NOx emissions for a High Velocity Nozzle Mix Burner at Various Hydrogen Mixtures and Pre-Heated Air Temperatures taken at the Lotte, Germany Test Facility



It should be noted that NOx numbers for hydrogen combustion should always be reported on a mass per energy unit basis, not in ppm at a reference oxygen level. It is industry standard to convert measured emission values to a reference oxygen level in order to properly compare emissions of burners in varying applications. This is a good way of accounting for high levels of oxygen in the flue gas present in some applications which serves to dilute the measured emissions and obscure the burner's actual performance. Implicit in this correction is that the burners whose emissions are sampled have the same volume of products of combustion. This is an accurate enough assumption if the burner is using a hydrocarbon fuel, but this assumption is not accurate for hydrogen combustion. For example, two identical burners are both running at the same capacity and air fuel ratio (0.5 MMBtu/hr at an excess air of 15% **Table 3.**), one of the burners is running hydrogen, and the other natural gas; the volume of dry products of combustion generated from the burner running 100% hydrogen is about 30% lower than the dry volume of combustion products for the burner running 100% natural gas. This means measured ppm emissions for the hydrogen burner would appear about 30% higher, while both burners true emissions measured on a mass per energy unit basis are identical. An example of this scenario can be seen in **Table 3.** This is an important and practical point to consider when switching from a hydrocarbon fuel to a hydrogen mixture with an existing industrial burner.

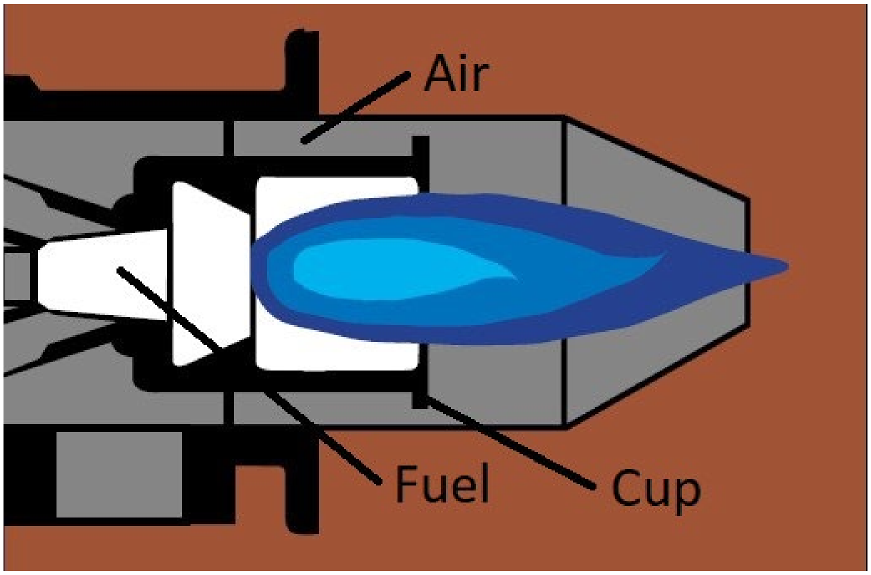
Table 3. Comparison of ppm and Mass Per Energy Unit Emissions for the Same Burner Running at the Same Capacity and Excess Air

Capacity (MMBTU/hr)	H2 Molar Fraction	Excess Air (%)	Dry Comb. Products Flow Rate (SCFH)	O2 (% vol dry)	NOx (ppm)	CO (ppm)	NOx (lb/MMbtu)	CO (lb/MMbtu)
0.500	0.000	15.0	4946.486	3.00	40.00	20.00	0.0480	0.015
0.500	1.000	15.0	3483.452	3.34	56.80	28.00	0.0480	0.015

Cup Mix Burners

Cup mixing burners mix the fuel and air at the point of ignition just as nozzle mix burners do, but they do not utilize a fuel nozzle with integral orifices to control the fuel velocity. These burners instead use a simple fuel orifice just upstream of the burner fuel inlet. This fuel orifice provides some pressure drop and limits the maximum fuel flow rate through the burner but does not tightly control the velocity of the fuel when it is introduced to the air. This makes these types of burners much more tolerant to changes in fuels because they do not rely on controlling the fuel velocity to create the desired fuel and air mixture. The air mixing device in these burners is a cup like structure, which tightly controls the amount and velocity of air through the burner (**Figure 10.**). Cup mixing burners can typically operate throughout a wider range of air fuel ratios compared to most nozzle mix burners. However, cup mixing burners also typically have a more limited thermal turndown compared to nozzle mix burners, in the range of 10:1.

Figure 10. Cup Mix ThermJet Burner Cross Section

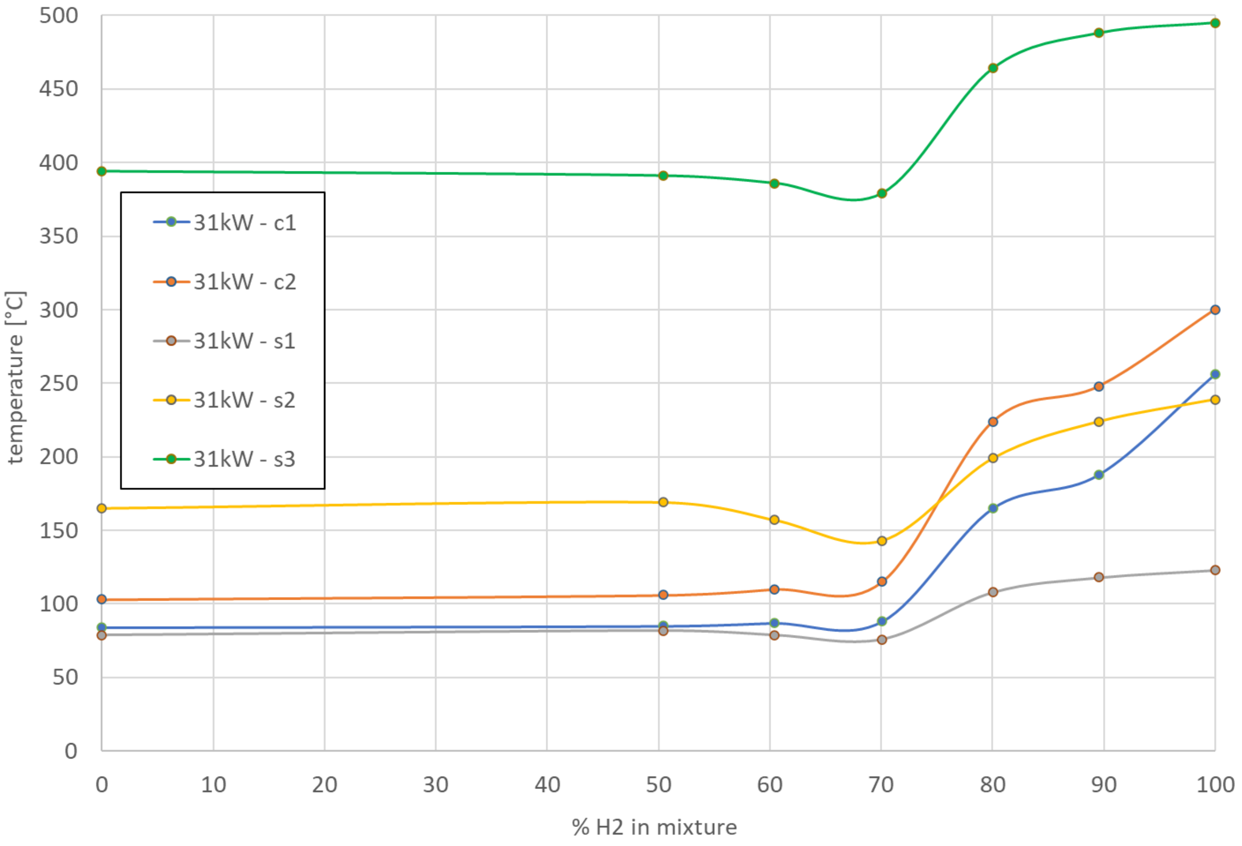


Cup Mix- Flame Stability on Hydrogen

We will apply the same principles as described in the nozzle mix section to the cup mixing burner. The increase in fuel velocity/flow rate through the cup mixing burner with the addition of hydrogen is not as disruptive to the normal mixing behavior of the burner, because it does not rely on the fuel velocity to properly mix the fuel and air. If the cup mixing burner was designed to run stoichiometric and the fuel was changed to hydrogen, the burner will now be running at 41% excess air, just as before, and will remain lit and stable. Cup mixing burners are normally paired with a ratio regulator which senses the air pressure at the blower and adjusts the fuel pressure by a constant ratio. It is essentially a dome-loaded pressure regulator that provides a simple, mechanical way of modulating fuel flow in a burner without using control valves. This ratio regulator is paired to the fuel orifice to provide the correct flowrate of fuel at the burner's maximum capacity. If the available fuel pressure cannot provide the higher flowrate of hydrogen through the fuel orifice at the available pressure, then the maximum capacity of the burner would be reduced. These fuel orifices are sized based on the burner's application so this point must be analyzed for a particular application before a fuel change to 100% hydrogen can be made for a cup mixing burner.

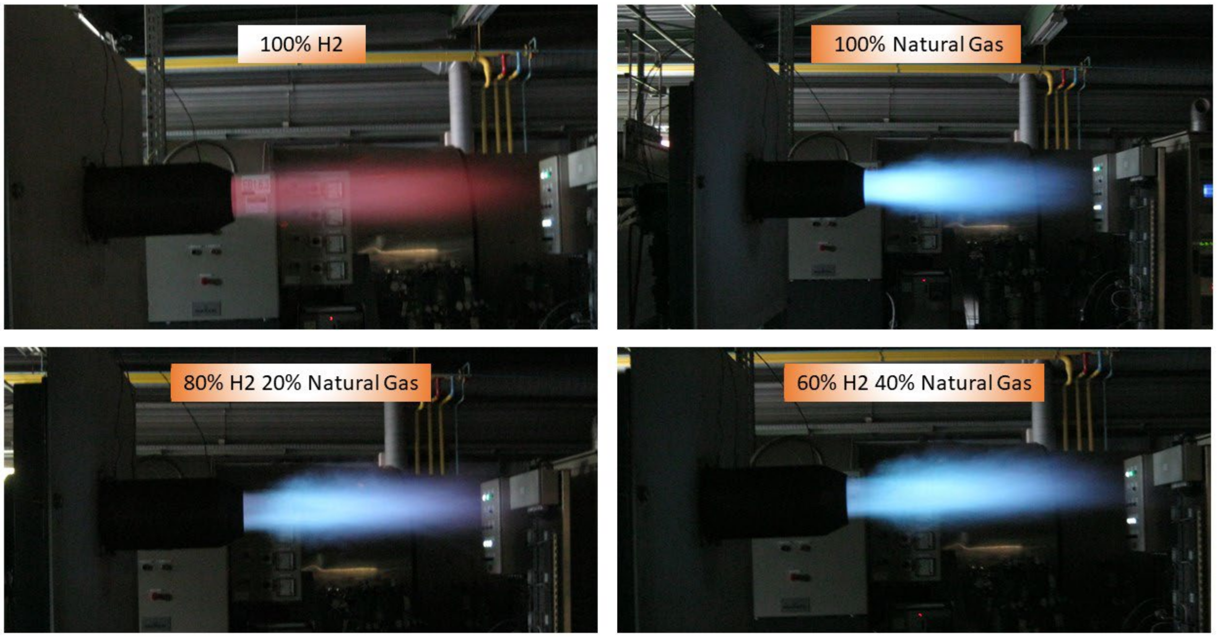
The way cup mixing burners handle the extra heat from the hydrogen flame is still the most critical factor in determining the cup mixing burner capability in burning hydrogen. The burner cup will still see elevated temperatures compared to natural gas combustion due to hydrogens higher flammability limits and concentrated heat release pattern. **Figure 11.** shows cup temperatures as a function of hydrogen percentage for a typical cup mixing burner firing into an air-cooled tube chamber. This testing done at the Vilvoorde, Belgium facility shows a 100 °C difference between 0% hydrogen and 100% hydrogen at the hottest point in the cup.

Figure 11. Cup Temperatures with Varying Hydrogen & Natural Gas mixtures on a Cup Mixing Burner at 0.105 MMBtu/hr (31kW) with 30% Excess Air taken at the Vilvoorde, Belgium facility



The flame geometry of a cup mix burner with high hydrogen mixtures is not significantly different than the nozzle mix flame geometry on high hydrogen mixtures. **Figure 12.** Shows a cup mixing burner firing different hydrogen mixtures in the open air.

Figure 12. Cup Mixing Burner with Varying H2 and Natural Gas Mixtures in the Open Air at the Vilvoorde, Belgium facility



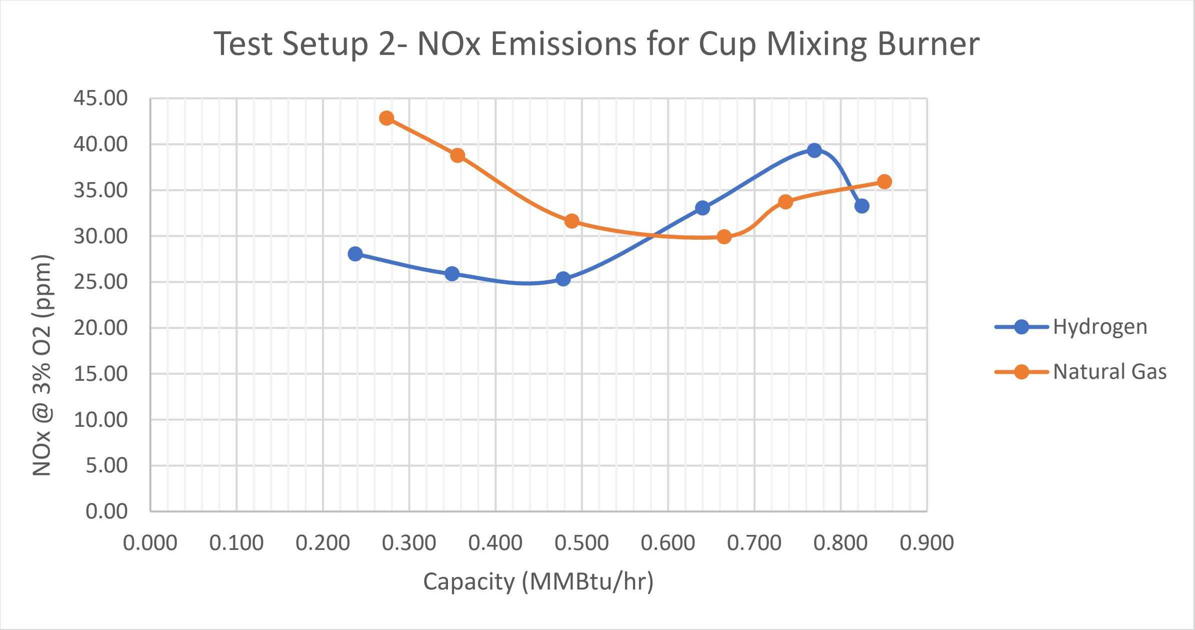
Cup Mix- Thermal Turndown

The thermal turndown of a cup mix burner firing hydrogen is not significantly different than the same burner firing natural gas. Due to the reasons described above a cup mix burner running hydrogen can operate in same range of air flow rates as a burner designed for natural gas and remain lit and stable. Forgetting all other considerations (heat buildup, resonance etc.) the addition of hydrogen would extend a cup mix burner's flexibility. This could be due to hydrogen's high diffusivity coefficient in air which allows higher percentages of excess air to be used and still maintain proper mixture properties.

Cup Mix- Emissions

Cup mix burners have the same challenges with NOx emissions that nozzle mix burners have, but they have one advantage, their ability to run with very high excess air levels. In certain industrial burner applications, excess air serves to decrease flame temperature and NOx. With higher hydrogen mixtures comes higher local flame temperatures and therefore higher excess air required to keep the flame temperature down. Burners that can remain lit and stable with high amounts of excess air can mitigate the worst effects of the hydrogen flame on NOx. **Figure 13.** was generated from Test Setup 2 and shows NOx emissions from a cup mixing burner running 100% hydrogen and 100% natural gas. Test Setup 2 consisted of a cup mixing burner being fired into a test chamber with a process velocity moving perpendicular to the burner discharge. Emissions data was taken at the stack. The burner was operated with fixed air, modulating only the fuel. For example, at a capacity of 0.639 MMBtu/hr the excess air for 100% natural gas was 251%, and the excess air at 100% hydrogen was 367%.

Figure 13. NOx Emissions for a Cup Mixing Burner in a Process Air Stream at the Muncie, Indiana Facility

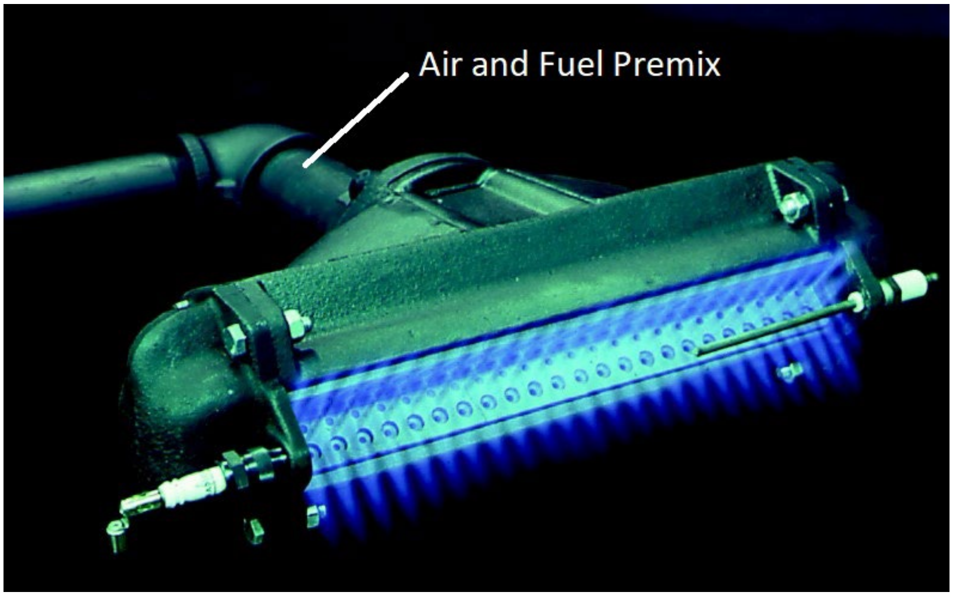


The high level of excess air brings the higher hydrogen flame temperatures down to a level which is on par with the cup burner's NOx emission performance on natural gas. It should be noted that the hydrogen data from Test Setup 2 was taken from a burner that had been modified to fire 100% hydrogen. This modification did not significantly change the combustion characteristics of the burner and were made largely due to excess heat on the burner cup when firing high hydrogen mixtures.

Premix and Partial Premix

Premix burners mix the fuel and air prior to ignition. This strategy brings favorable mixture qualities, but at the cost of thermal turndown. Premix burners will stabilize at the point where the flame velocity matches the velocity of the mixture, and the fuel and air mixture is within the flammability limit of the fuel. In practice premix burners are designed to create this condition at a designated location by using a flame stabilizing device. If the velocity of the mixture is lowered enough that this condition is met upstream of the flame stabilizing device the flame will flashback and anchor there. If the velocity of the mixture is raised enough, the flame will be unable to anchor anywhere and will blowoff. The thermal turndown of a premix burner is therefore limited by the flame velocity of the fuel, and its flexibility in air fuel ratios is limited by the flammability limits of the fuel. Thermal turndowns of premix burners are in the range of 4:1 to 8:1.

Figure 14. Premix LinoFlame Burner

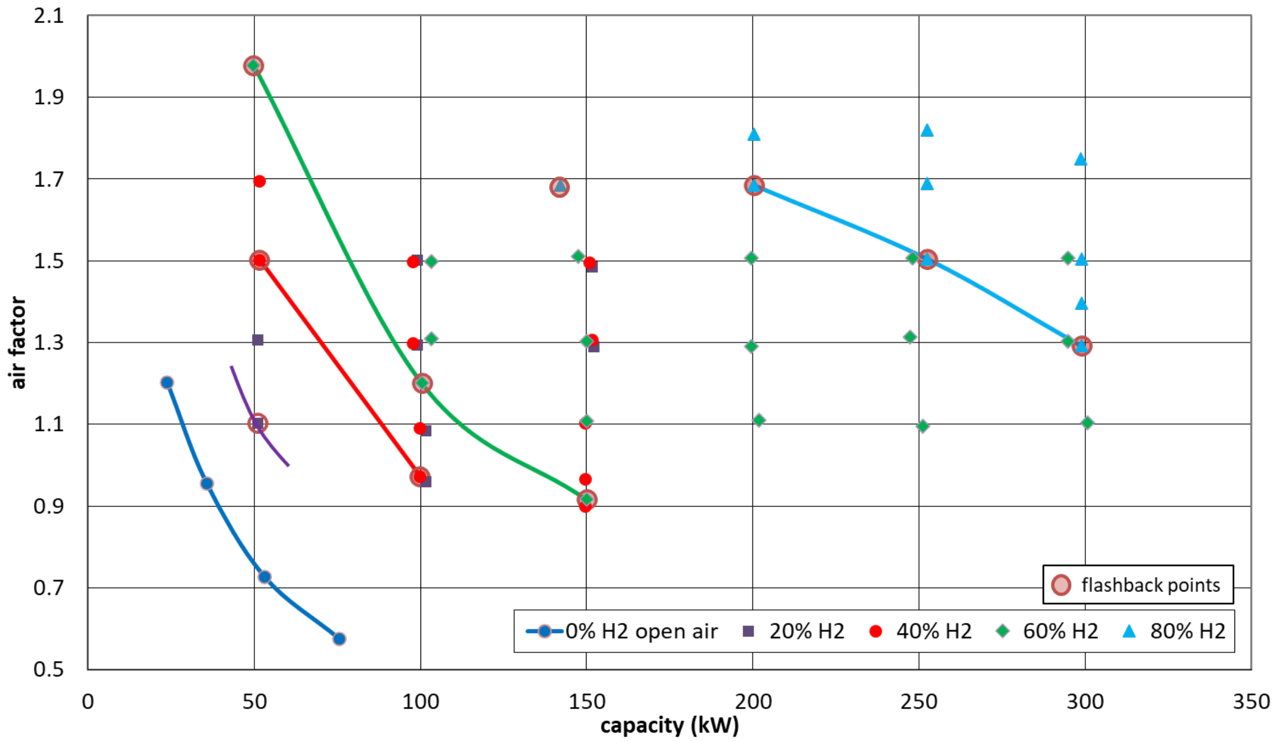


Partial premix burners combine premix and nozzle mix strategies. A portion of the fuel is introduced prior to ignition and the remaining fuel is introduced at the point of ignition. Partial premix burners combine the mixture benefits of premix, with some of the thermal turndown of a nozzle mix burner. Partial premix burners have a flame stabilizing device, but also don't introduce enough fuel to create a flammable mixture upstream of the stabilizing device, eliminating the possibility of flashback beyond this point. Thermal turndown for partial premix burners are in the range of 20:1.

Premix and Partial Premix- Flame Stability on Hydrogen

Switching a premix and partial premix industrial burner from natural gas to high percentages of hydrogen without changing fuel and air ratio will likely result in a loss of flame. Hydrogen has a significantly higher flame velocity than natural gas, as well as a wider flammability range. The higher flame velocity would likely result in the low velocity region created by the flame stabilizer being no longer sufficient to maintain the hydrogen flame, resulting in flashback. A stable flame may be created by adjusting the fuel and air ratio, providing the combustion system has enough flexibility to create the proper conditions. **Figure 15.** shows the results of testing done at the Vilvoorde, Belgium facility on the flame stability limits of a premix industrial burner. The testing was conducted in the open air with varying levels of hydrogen and natural gas mixtures, as well as varying fuel and air ratios ($\emptyset = 2$ to $\emptyset = 0.5$). The burner's maximum capacity was 2.4 MMBtu (705 kW), with a thermal turndown of 20:1. The lines on the graph indicate the lowest capacity possible and its corresponding air and fuel ratio setting. The blowoff limit was not tested. As the hydrogen percentage increases the lowest possible capacity for the burner increases, and more air is required to achieve a stable flame at that point.

Figure 15. Premix Industrial Burner Flame Stability Limits on Hydrogen and Natural Gas Mixtures done at the Vilvoorde, Belgium facility



Full premix burners should not have the same issues nozzle mix and cup mix burner have with hydrogens concentrated heat release pattern and higher flame temperature. Premix flames propagate over a distance which allows the excess air more opportunity to keep the flame temperature down. Partial Premix burners however will display similar issues seen with nozzle mix because they typically have a fuel nozzle. These fuel nozzles will see elevated temperatures due to the hydrogen flames concentrated heat release pattern compared to natural gas combustion.

As has been noted with nozzle mix and cup mix burners, the flame geometry does not significantly change with high hydrogen mixtures. **Figure 16.** Shows as premix burner firing varying mixture of hydrogen and natural gas into the open air.

Figure 16. Premix Burner with Varying H2 and Natural Gas Mixtures in the Open Air at the Vilvoorde, Belgium facility

Premix and Partial Premix - Thermal Turndown

If the air fuel ratio was adjusted to maintain a high hydrogen content flame for a premix and partial premix industrial burner, then the thermal turndown would be significantly limited by the wider flammability limits of hydrogen. The hydrogen premix flame would be prone to flashback at fuel flow rates that previously produced a stable flame with natural gas. Thermal turndown can be expected to be reduced significantly depending on the mixture of hydrogen used. **Figure 15.** shows thermal turndown to be reduced by 7 times from 0% hydrogen to 80% hydrogen.

Premix and Partial Premix – Emissions

If properly designed to maintain the hydrogen flame, premix industrial burners should not see a significant increase in NOx when burning hydrogen. Since the premixed flame propagates across a distance the excess air will have a greater ability to reduce the flame temperature compared to nozzle and cup mix burners. The type of partial premix burner would determine effect of burning hydrogen on emissions. If the partial premix burner was able to handle high amounts of excess air and the fuel nozzle could be kept for seeing excess heat, then NOx emissions should not increase, as described above and shown in **Figure 13.**

Conclusions

Each of the three fuel and air mixing strategies for industrial burners have advantages and disadvantages when burning hydrogen as a fuel. Which strategy is best suited will depend on the application requirements and the range of hydrogen mixture percentages to be supplied to the burner. If existing industrial burners designed for natural gas combustion are supplied with hydrogen mixtures above 50% hydrogen without any design changes, then nozzle mix, or cup mix are the strategies which show the most promise. At higher hydrogen percentages excess heat on the burner components becomes a concern, and high air velocity or higher amounts of excess air will be required to dissipate the extra heat. Some nozzle mix and cup mix burner designs will not be capable of removing the extra heat on the burner components, depending on the overall design of the burner, but due to their flexibility in air fuel ratios provide the most promise in doing so. Premix and partial premix industrial burners are not good candidates for high amounts of hydrogen in the fuel supply. At higher percentages of hydrogen, they are susceptible to flashback and loss of flame, severely reducing their operating range.

Supplying varying high hydrogen mixtures to industrial burners with no modification is not the ideal scenario and has some disadvantages to the performance of the burner as described above. This scenario limits the burners available for hydrogen combustion to the types which are most flexible in their viable air fuel ratios. However, if a fixed percentage of hydrogen can be supplied to the burner, then most burner designs utilizing any of the three strategies explored in this report can be modified/retrofitted to accommodate hydrogen combustion. This type of modification is very common for industrial burners that need to use local gas types with hydrocarbon mixtures that differ from natural gas, or for burners which need to utilize propane of butane as a fuel. The overall performance of the burner will be greatly increased if design changes can be made to accommodate hydrogen's unique properties.

NOx emissions for nozzle mix and cup mixing burners designed for natural gas can be expected to increase when burning hydrogen, unless the higher local flame temperatures of the hydrogen flame can be mitigated with excess air. With increasing hydrogen percentages in the fuel supply more and more excess air is required for most nozzle mix and cup mix burners to mitigate the higher local flame temperatures. Burners that can remain stable with very high amounts of excess air can maintain NOx performance with high hydrogen fuel blends. However, in applications that cannot tolerate higher oxygen levels, NOx will likely increase when burning higher hydrogen mixtures using the three designs explored here.

The three mixing designs explored here do not represent every industrial burner on the market. There are a wide variety of designs which produce low NOx, or high efficiency with novel techniques not discussed in this report. The goal of this report was not to find the optimal design of industrial burner for hydrogen combustion, but to give an overall view on the effects of hydrogen fuel blends would have on a large majority of industrial burners. However, the fundamental characteristics of hydrogen combustion are common among all burner designs and the success of a particular design relies on the way it balances those characteristics against the requirements of its application.

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